Particle Physics Ideas for Dark Matter and Dark Energy

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SNAP Cosmology Teach-In, LBNL

Introduction - I

- **QUESTION:** What is the Universe made of?

- Particle physicists' answer: particles!!!

- Standard Model of particle physics:

  - 6 quarks ($\Longrightarrow \sim 100$ mesons and baryons: $p, n, \pi, K, \ldots$)

  - 3 charged leptons: e, μ, τ

  - 3 neutrinos: ν_e, ν_μ, ν_τ

  - 4 gauge bosons: γ, Z, $W^\pm$

  - 1 scalar boson: the Higgs H (?)

- Most of these particles are unstable, with $\tau < 1$ sec, and require at least 1 GeV of energy to be produced $\Longrightarrow$ will not be present in a $\sim 10^{10}$-year old Universe with a temperature of $\sim 10^{-4}$ eV

- Exceptions: p, n (when bound in a nucleus), e, ν, and γ are stable

- A naive particle physicist would expect the Universe to be made of these five!

Introduction - II

- Cosmologists' answer: look at the data!
  - The universe is flat, or very nearly flat:

    $$\Omega_{tot} = 1.02 \pm 0.02$$

    from CMBR anisotropy measurements (WMAP, 2003) $\Longrightarrow$ the total density is very close to critical.
  - Non-relativistic matter (stars, galaxies, people, ...) contributes about 30% of the total – from gravitational dynamics of galaxy clusters + CMBR anisotropy.
    - Out of this 30%, only about 5% is contributed by baryons (protons and neutrons) – from Big Bang nucleosynthesis + CMBR anisotropy.
    - The Universe is electrically neutral $\Longrightarrow$ only about 0.01% is contributed by electrons
    - The other 25% is **DARK MATTER**
  - Radiation (photons) contributes a very small amount – about 10^{-4} of the total.
  - The remaining 70 % is a new, non-luminous, non-clustering component of the universe – **DARK ENERGY** (SCP, High-ZSN, 1998)
- Only 5% is made out of p, n, e, γ!
- What about neutrinos?

Neutrinos - I

- Massless (or very light) neutrinos, $m_\nu < 10^{-4}$ eV, would behave as radiation, contribute $\sim 10^{-4}$ of the critical density $\Longrightarrow$ not very interesting.

- Heavier ν's behave as non-relativistic matter $\Longrightarrow$ could contribute to dark matter!

- Neutrino oscillations prove that neutrinos have non-zero masses (SuperK, 1998; SNO, 2001; KamLAND, 2002)

- Oscillations observed: $\nu_\mu \leftrightarrow \nu_\tau$ (atmospheric), $\nu_e \leftrightarrow \nu_{\mu,\tau}$ (solar)

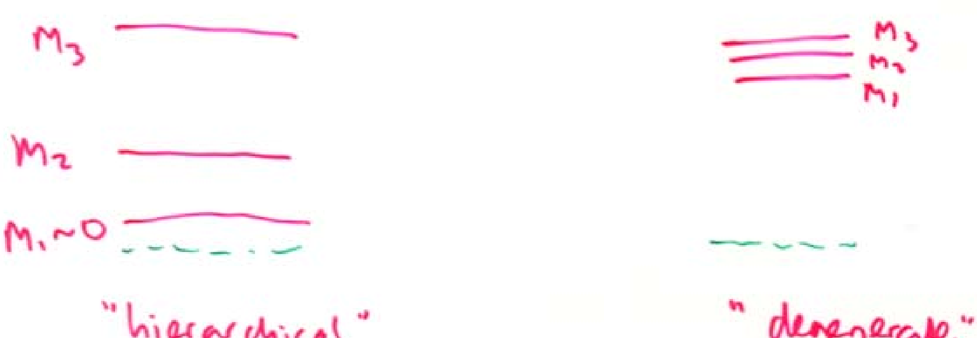
- Oscillation experiments are sensitive to mass differences between different flavors:

$$\Delta m^2_{atm} \approx 3 \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{sol} \approx 4 \times 10^{-5}\ \mathrm{eV}^2$$

- The overall mass scale is not fixed; still, at least 2 ν's must be non-relativistic!

- Precision studies of tritium β decay spectrum: $m_{\nu_e} < 3$ eV



Neutrinos - II

- Neutrino density $\Omega_\nu = \rho_\nu/\rho_c$ can be calculated:
  - In the early Universe, ν's are thermalized by weak interactions: e.g.

$$\nu + e \leftrightarrow \nu + e$$

  - At that time, the density is known from thermodynamics:

$$n_\nu = \frac{3\zeta(3)}{2\pi^2} T^4$$

  - The scattering rate is roughly

$$\Gamma \sim G_F^2 T^5$$

  - Expansion rate in the early (RD) Universe:

$$H \sim T^2/M_{Pl}$$

  - Neutrinos decouple (drop out of thermal equilibrium) when

$$\Gamma \sim H \quad \Longrightarrow \quad T \sim 1 \text{ MeV}$$

  - After that, $n_\nu \propto T^{-4}$ for $T > m_\nu$ and $n_\nu \propto T^{-3}$ for $T < m_\nu$.
  - The answer (for each ν species):

$$\Omega_\nu h^2 = \frac{m_\nu}{91 \text{ eV}}$$

- Degenerate ν's with $m_\nu \approx 3$ eV could provide enough dark matter!

Neutrinos - III

- However, the νDM hypothesis contradicts the CMB and large-scale structure data!

- Inflationary paradigm:

  - Quantum fluctuations created during inflation...

  - Lead to inhomogeneities in the cosmic fluid after reheating ($t \sim 10^{-37}$ sec.) with adiabatic, scale-invariant spectrum...

  - Which lead to the CMB anisotropies ($t \sim 10^5$ yrs)...

  - And ultimately to the formation of galaxies, clusters, etc. ($t \sim 10^9$ yrs).

- After $t \sim 1$ sec, ν's do not move with the rest of the cosmic fluid

- 3 eV ν's are relativistic until $t \sim 10^4$ yrs $\Longrightarrow$ "free-stream", partly erasing the inhomogeneities

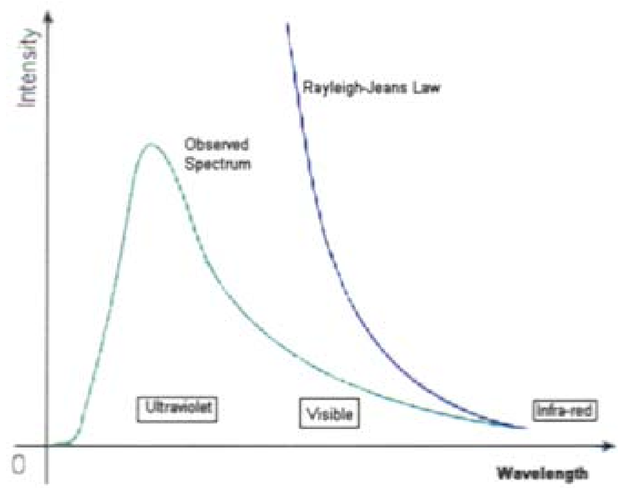
- Large $\Omega_\nu \Longrightarrow$ deviations from the scale-invariant spectrum $\Longrightarrow$ inconsistencies with CMB, LSS

- Upper bound: $\Omega_\nu h^2 < 1\%, \Sigma\, m_\nu < 0.7\,\mathrm{eV}$ (WMAP + 2dFGRS, 2003)

- FIASCO of the SM: the five stable particles together account for only 6% of the matter in the Universe!

Beyond the SM I

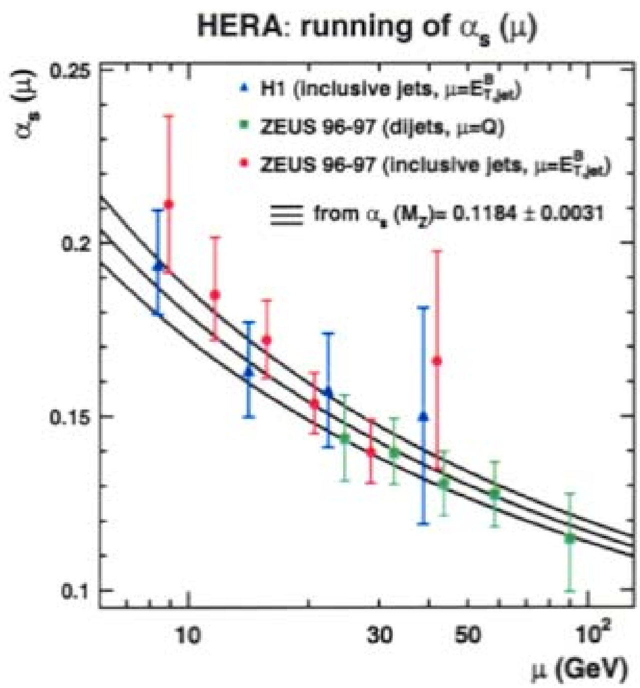
- Computing quantum corrections in most field theories (including SM) involves integrals which diverge at high virtual momenta
- Mathematically, this can be dealt with by renormalization
- Physically: divergences $\Longleftrightarrow$ applying a theory where it's no longer valid



- Expect a deeper layer of structure beneath the Standard Model (at shorter distances/higher energies)
- Guess: the more fundamental theory will also incorporate gravity
- String theory is finite and contains gravity $\Longrightarrow$ the best candidate for the "ultimate" theory
- Intrinsic scale of gravity: the Planck scale, 10^{-33} cm or 10^{19} GeV (or, 1000000000000000 times higher than the LHC!)
- Can the SM be a valid effective theory up to the Planck scale?

Beyond the SM II

- All parameters of QFTs (masses, coupling constants) depend on the energy scale at which they are measured ("running")



- Fundamental theory determines the "bare" values of parameters at the cutoff scale E_c (the scale at which the SM breaks down)
- Bare values + running $\Longrightarrow$ the observed values at $\mu \ll E_c$
- For all SM parameters, the running is weak (logarithmic):

$$\alpha(\mu) = \alpha(\Lambda) + \frac{\alpha^2}{4\pi} \log\left(\frac{E_c}{\mu}\right)$$

Beyond the SM III

- EXCEPTION: the Higgs mass runs very fast ("instability")

$$m^2(\mu) = m^2(E_c) - \frac{3\lambda_t^2}{16\pi^2}\left(E_c^2 - \mu^2\right)$$

- Correct description of the Weak force requires

$$m^2(\mu = 100 \text{ GeV}) \approx (100 \text{ GeV})^2$$

- Assuming $E_c \approx M_{Pl}$, the running term is about 10^{30} times too big
- Can be cancelled by fine-tuning the bare mass term, $m^2(E_c)$, at 10^{-30} level...
- BUT, how does the fundamental theory "know" about running at low energies?
- No examples of such cancellations in any known effective field theory
- A much more reasonable alternative: $E_c \approx 1$ TeV $\Longrightarrow$ SM breaks down, new physics appears at energy scales about 1 TeV
- The new physics "stabilizes" the Higgs mass $\Longrightarrow$ part of the electroweak symmetry breaking mechanism
- The TeV energy scale is accessible to the LHC $\Longrightarrow$ discoveries beyond the SM Higgs are very likely

Beyond the SM - IV

- In the meantime, theorists try to guess!
- Guidance: need to stabilize m_H ("solve the hierarchy problem")
- Options for the theory beyond 1 TeV:
  - Field theory with no Higgs boson (technicolor)
  - Field theory, Higgs boson is there but its mass does not run fast (supersymmetry, little Higgs)
  - Not a field theory at all (extra dimensions)
- Each of these options has experimentally observable consequences $\Longrightarrow$ testable at the LHC
- Each has multiple new particles, typically in the 100 GeV – 1 TeV mass range
- Can these particles be dark matter?

BSM Dark Matter I

- General requirements on a "dark matter candidate" X:
  - X has to be stable (or at least have $\tau > 10^{10}$ yrs)
  - X cannot have strong interactions: otherwise pX exotic nuclei
  - Neutrality $\Longrightarrow$ X cannot be electrically charged (unless also have Y of the opposite charge!)

- Calculate the abundance of a weakly-interacting particle X with mass m in the 100 GeV – 1 TeV range (WIMP):
  - Interaction rate for $T \lesssim M_E W$:

$$\Gamma \sim n_X \,\sigma \sim n_X / M_{EW}^2$$

  - Decoupling: $T_d \sim m \sim M_{EW}$
  - Abundance at decoupling:

$$\Gamma \sim H \quad \Longrightarrow \quad n_{X,d} \sim \frac{M_{EW}^2 T_d^2}{M_{Pl}}$$

  - Abundance today:

$$n_{X,0} = n_{X,d} \left(\frac{T_d}{T_0}\right)^3 \sim \frac{M_{EW} T^3}{M_{Pl}}$$

  - Energy density in WIMPs today:

$$\rho_{X,0} = m \, n_{X,0} \sim \frac{M_{EW}^2 T^3}{M_{Pl}}$$

  - Numerically,

$$\rho_{X,0} \sim \rho_{crit,0}$$

  – a pretty amazing coincidence!

BSM Dark Matter II

- WIMP decouples from thermal plasma when it is non-relativistic $\Longrightarrow$ no free-streaming!
- WIMP (or a "stable Z boson") would be an ideal dark matter candidate!
- Almost all BSM theories have WIMPs; the issue is stability
- Stability typically requires a conserved quantum number
- "Dark Matter Parity" (conserved in the SM):

$$Z_{DM} = (-1)^{3(B-L)+2S}$$

- $Z_{DM} = 1$ for all SM particles...

BSM Dark Matter III

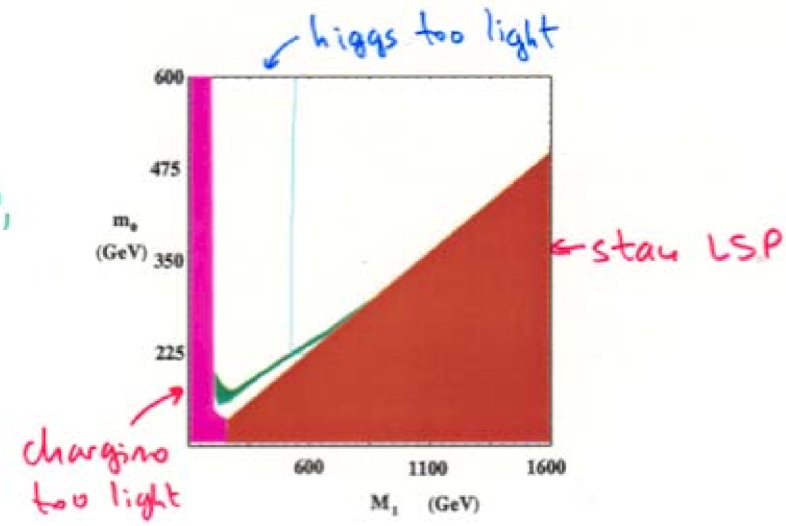
- Supersymmetry: bosons (spin-0,1) $\Longleftrightarrow$ fermions (spin-1/2)
- SM particles have superpartners: sleptons, squarks, gauginos
- Superparticles have not been seen yet — too heavy
- Superparticles have same B, L, but S differs by $1/2 \Longrightarrow$ they have $Z_{DM} = -1 \Longrightarrow$ the lightest superparticle (LSP) is stable!
- If the LSP is uncolored and electrically neutral, it provides a perfect WIMP candidate
- Four superpartners with the right quantum numbers: Photino, Zino, Higgsino ($\Longrightarrow$ Neutralino), Sneutrino
- The nature, mass, cross-sections of the LSP are model-dependent
- Neutralino tends to be the most attractive candidate
- Many detailed studies of the neutralino abundance (Ellis, Olive, ..., 1990 – 2003)
- All are subject to significant uncertainties!
  - Assumptions about SUSY: $\sim$ 120 parameters $\Longrightarrow$ 2! (e.g. Birkedal-Hansen, Nelson, 2002)
  - Assume no entropy production in QCD phase transition (Birkedal-Hansen, MP, in progress)

BSM Dark Matter IV

MSUGRA

$\tan\beta = 5$, $A_0 = 0$,

$\mu > 0$

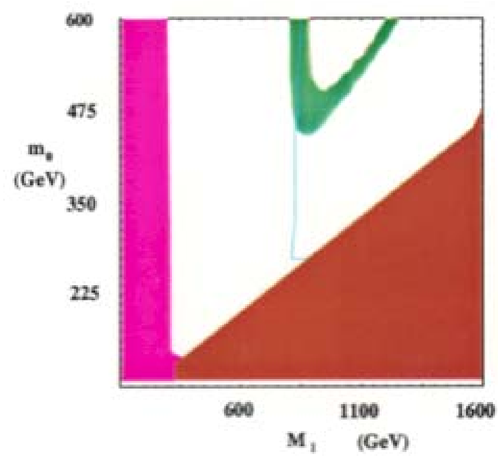


MSUGRA

w/ non-universal gaugino masses:

$M_2 = M_3 = 0.6\, M_1$

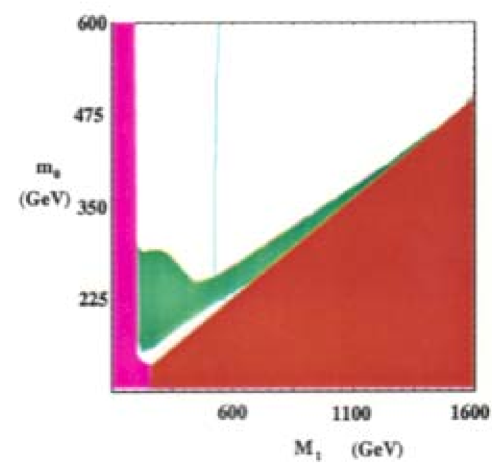
@ M_{GUT}



MSUGRA

+ 1st order QCD phase transition,

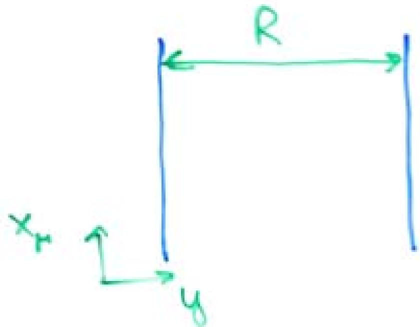
$\frac{\Delta S}{S} \simeq 2$



(Credit: Andreas Birkedal-Hansen)

BSM Dark Matter V

- Another possibility: extra dimensions!
- "Universal" extra dimensions, $R \sim 10^{-16}$ cm (Appelquist, Cheng, Dobrescu, 2000)



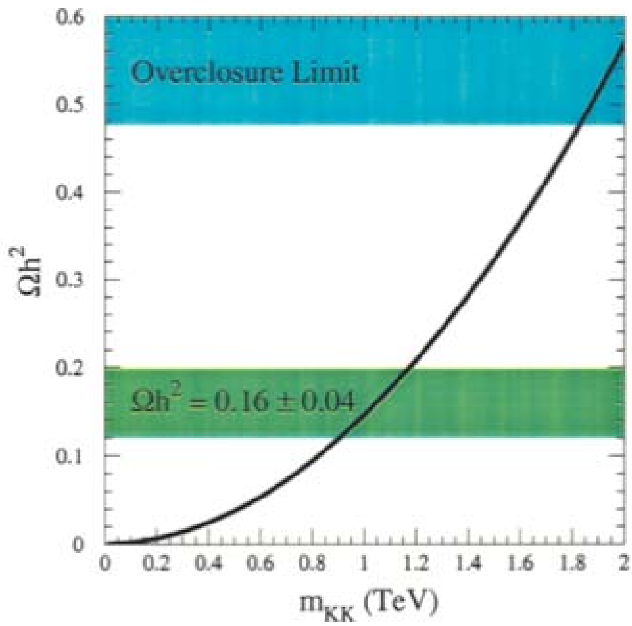
- Kaluza-Klein (KK) decomposition:

$$\phi(x,y) = \sum_n \phi_n(x) \exp\left(\frac{iny}{R}\right)$$

- Zero-modes (ϕ_0) $\Longleftrightarrow$ SM particles
- The first "KK excitation" (ϕ_1): $M \sim 1/R \sim$ TeV
- KK number $n \Longleftrightarrow$ momentum $k_5 \Longrightarrow$ conserved!
- The lightest KK particle (LKP) is stable
- Hierarchy of the KK masses is determined by radiative corrections (Cheng, Matchev, Schmaltz, 2002)
- For example, LKP could be KK neutrino ν_1 or KK photon γ_1 $(\sim B_1)$

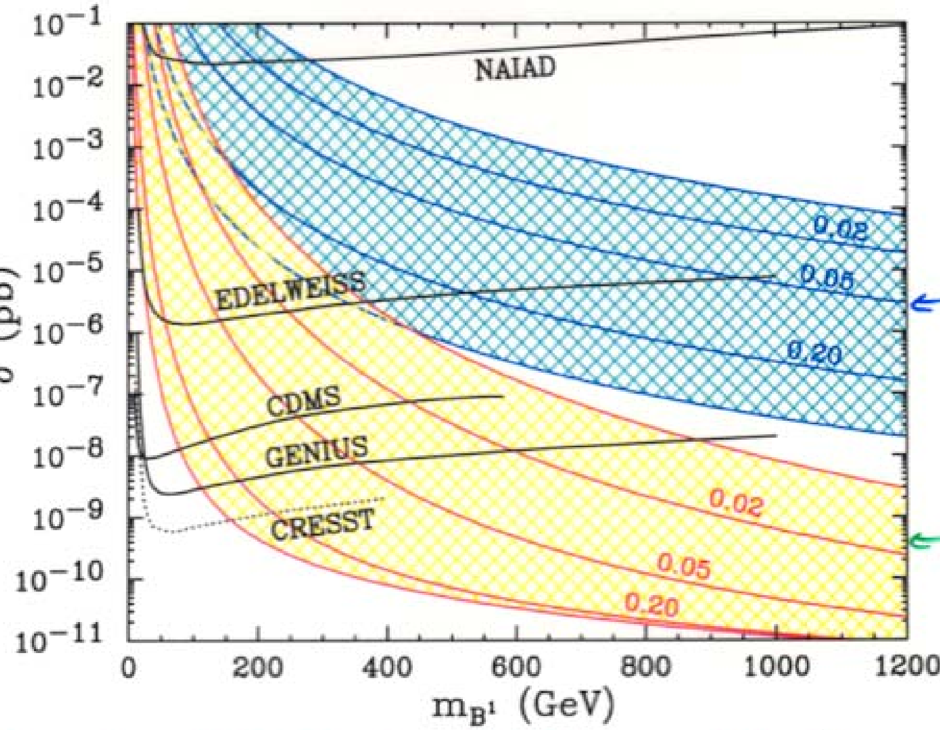
BSM Dark Matter VI

- Both particles can be dark matter with the correct abundance (Servant, Tait, 2002)



← for B_1 LKP

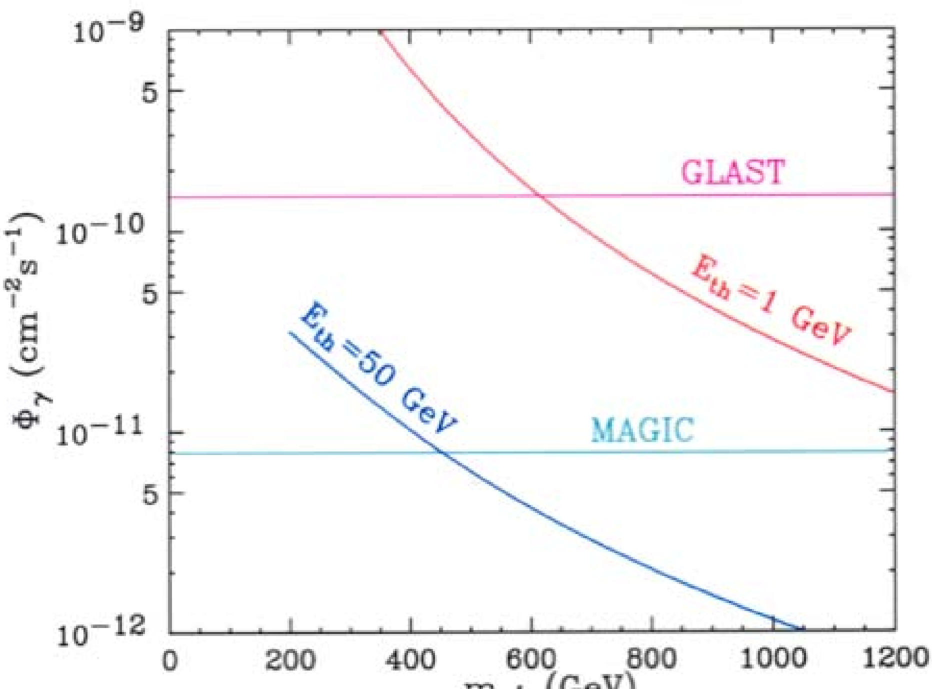
- Direct and indirect detection possible (Cheng, Feng, Matchev, 2002)



← spin-dep.

← spin-ind.

• Direct detection: $\sigma(B^1 + p \to B^1 + p)$



• Indirect detection: Φ_γ from $B^1 + B^1 \to \gamma + \gamma$

Dark Energy I

- Effective Field Theory (EFT) Approach: (Wilson, Weinberg, ..., 1970's)
  - All terms consistent with the symmetries of the theory should be included in the Lagrangian $\Longrightarrow$ infinite number of terms!
  - EFT breaks down at a high energy scale E_c, where it is superseded by a more fundamental theory
  - At low energies, $E \ll E_c$, only a finite set of "renormalizable" terms is important; others are suppressed by powers of (E/E_c) $\Longrightarrow$ predictivity!
- Standard Model is an EFT, with a cutoff $\sim$ TeV
- A constant term in the Lagrangian is consistent with all the symmetries $\Longrightarrow$ has to be included!

$$S = \int d^4x \sqrt{-g}\, \Lambda + \dots$$

- Physical meaning: Λ = vacuum energy (a.k.a. "cosmological constant")
- The only observable consequence of Λ: influences the expansion of the Universe
- Acts as a component with $w = -1$: could be dark energy!
- Attractive: does not require extending the SM!

Dark Energy II

- Just like the Higgs mass, Λ runs very fast:

$$\Lambda(\mu) = \Lambda(E_c) + \frac{g^2}{16\pi^2}(E_c^4 - \mu^4)$$

- Data: $\Omega_{DE} \approx 0.7$ (SN, WMAP) $\Longrightarrow$

$$\Lambda \approx (10^{-3}\ \mathrm{eV})^4$$

- This is a measurement of Λ at huge distance scales $\Longleftrightarrow$ very low μ, effectively $\Lambda(0)$

- Assuming $E_c \approx$ TeV, the running term is about 10^{60} times too big – much worse than the Higgs mass

- Again, can be cancelled by fine-tuning the bare term, $\Lambda(E_c)$, at 10^{-60} level

- This would require conspiracy between Hubble-scale and subatomic physics – no known examples in any EFT!

- This is the famous "cosmological constant problem"

- Unlike the Higgs mass case,

NO SOLUTION IS KNOWN!!!

- This problem severely limits particle physicists' ability to talk sensibly about dark energy...

...But does not stop them from doing so!

Dark Energy III

- Only two mass scales are believed to be "fundamental" in particle physics:
  - Electroweak symmetry breaking scale: $M_W \sim 1$ TeV - determines the range of the weak force
  - Planck scale: $M_{Pl} \sim 10^{18}$ GeV - determines the strength of gravity
- Dark energy seems to require a new "fundamental" mass scale:

$$\Lambda \approx (10^{-3}\ \mathrm{eV})^4$$

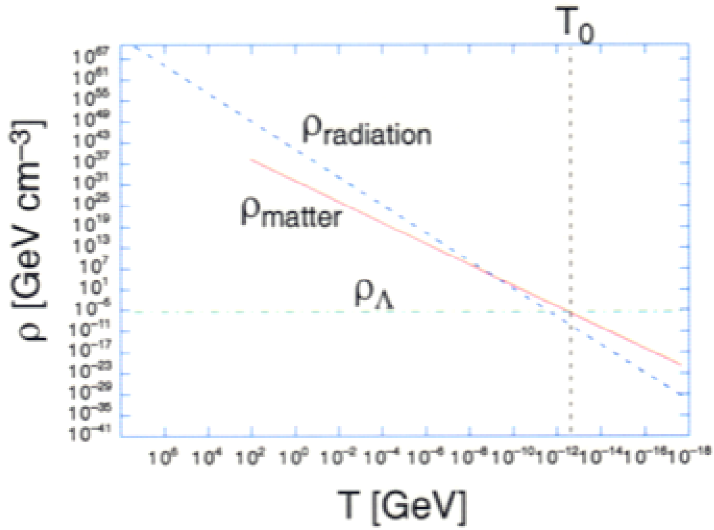
- An extremely intriguing coincidence - the "scale relation":

$$\Lambda \sim \left(\frac{M_W^2}{M_{Pl}}\right)^4$$

- Explaining the scale relation requires solving the c.c. problem!
- May provide an important **HINT**... but so far we haven't been smart enough to use it!
- Nevertheless, the scale relation led to some interesting speculations (Arkani-Hamed, Colda, Hall, Murayama, 2000)
  - New perspective on the "coincidence" problems
  - Multiple-vacuum models

Dark Energy IV

- Observation of dark energy has raised two interesting questions:



  - Why do the three lines almost meet? (the "triple coincidence problem")
  - Why do we live so close to the time when they met? (the "why now problem")

- Scale relation $\Longleftrightarrow$ Triple coincidence:
  - Matter density (for WIMPs):

$$\rho_m \sim \frac{M_{EW}^2 T^3}{M_{Pl}}$$

  - Radiation density:

$$\rho_r \sim T^4$$

  - Matter-radiation equality tempearture:

$$T_{eq} \sim M_{EW}^2 / M_{Pl}$$

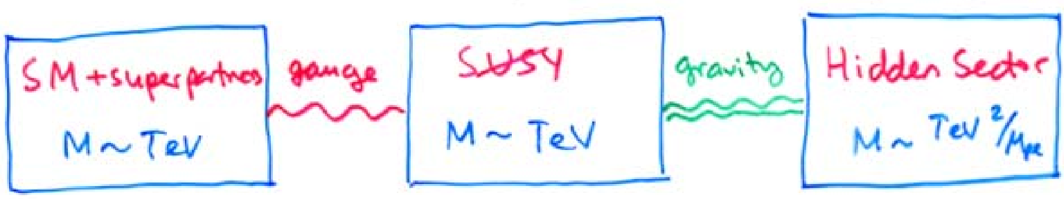
  - At T_{eq}, $\rho_\Lambda \sim \rho_{m,rad}$ if, and only if, the scale relation is satisfied!

Dark Energy V

- A theory explaining the scale relation will automatically resolve the triple coincidence problem!

- The why-now problem necessarily requires anthropic arguments...

- Partial explanation of the scale relation:
  - Consider a supersymmetric model with SUSY breaking at $\sim$ TeV
  - MSSM fields feel SUSY breaking via gauge interactions $\Longrightarrow$ superpartners at the TeV scale
  - Add a hidden sector which only feels SUSY breaking via gravity



  - Consider a hidden sector with multiple vacua, degenerate in the SUSY limit

  - Splittings between vacua are

$$V_m - V_n \sim \left(\frac{M_{EW}^2}{M_{Pl}}\right)^4$$

$\Longrightarrow$ scale relation!

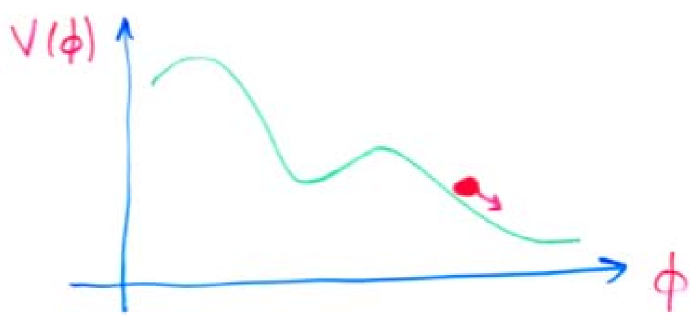
  - The overall scale has to be fine-tuned...

Quintessence I

- Vacuum energy has equation-of-state $w = -1$
- From data (SN, CMB, LSS)

$$w \lesssim -0.7 \qquad \text{at } 95\% \text{ c.l.}$$

- Logical possibility: $\Lambda \equiv 0$ (exact cancellation), dark energy is something else
- The most popular alternative: "scalar field quintessence"



- Evolution of a spacially-homogeneous scalar field in the FRW Universe:

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) \;=\; 0$$

- A simple example: quadratic potential

$$V = \frac{1}{2}\, m^2\, \phi^2$$

$\Longrightarrow$ harmonic oscillator with friction

- $m \gg H$: underdamped, $w_{eff} = 0$
- $m \ll H$: overdamped, $w_{eff} = -1$
- $m \sim H$: critically damped, quintessence

Quintessence II

- Quintessence models require

$$m_q \sim H \sim 10^{-33}\ \text{eV}$$

- This is the low-energy mass, effectively $m_q(0)$

- Scalar field $\Longleftrightarrow$ instability (remember the Higgs!)

- Without a stabilization mechanism, requires fine-tuning to one part in 10^{90}!

- The problem applies to any potential: e.g.

$$V(\phi) = \mu^4 e^{-\phi/M} \approx \mu^4 \left(1 - \frac{\phi}{M} + \frac{1}{2}\frac{\phi^2}{M^2} + \ldots\right)$$

$\Longrightarrow$ instability in both μ and M

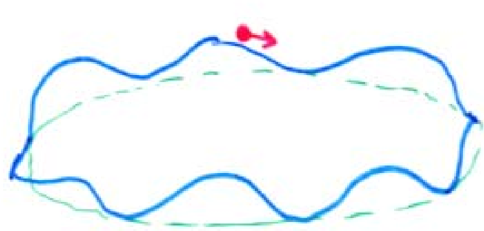
- Challenge: to construct radiatively stable (or "natural") models of quintessence

- An idea that does **NOT** work: supersymmetry
  - In real world, SUSY is broken at least at $\sim$ TeV
  - Any field has at least gravitational-strength interactions with the SUSY-breaking fields (gravity is universal!)
  - The minimal mass that can be protected by SUSY:

$$m_{min} \sim \frac{\text{TeV}^2}{M_{Pl}} \sim 10^{-3}\ \text{eV} \gg m_q$$

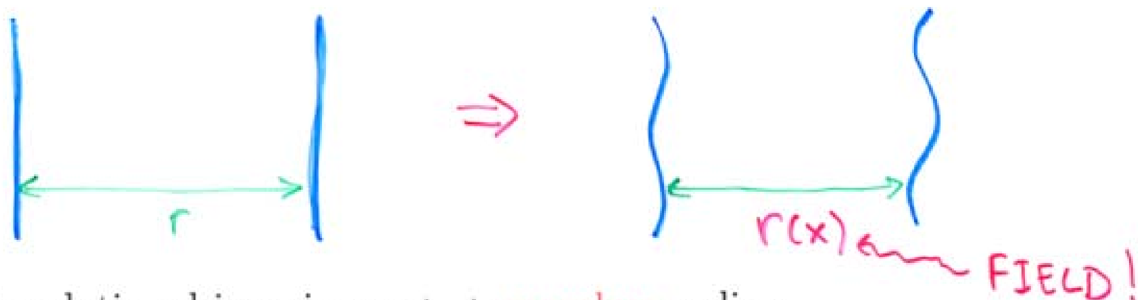
Quintessence III

- A better idea: axion quitessence (e.g., Nomura, Watari, Yanagida, 2000)
  - A scalar can be massless if it is a Goldston boson due to an exact global symmetry: Symmetry $\Longrightarrow$ stability
  - Small symmetry breaking $\Longrightarrow$ small mass
  - Example: Peccei-Quinn axion
$$m_a \sim \frac{\Lambda_{QCD}^2}{f} \gtrsim 10^{-12}\ \mathrm{eV}$$
  - QCD confinement scale arises from dimensional transmutation:
$$\Lambda_{QCD} \approx M_{Pl} \exp(-\frac{2\pi}{\alpha_s(M_{Pl})\beta})$$
  - An $\mathcal{O}(1)$ change in β can give a huge change in Λ_{QCD}
  - Imagine a new QCD-like sector (none of the SM particles are "colored") with $\Lambda_{new} \sim 10^{-33}$ eV
  - The axion of that sector could be quintessence, naturally
  - Axion potential:
$$V(a) = \Lambda_{new}^4 \cos \frac{N_{\mathrm{PQ}}\, a}{f}$$



Quintessence IV

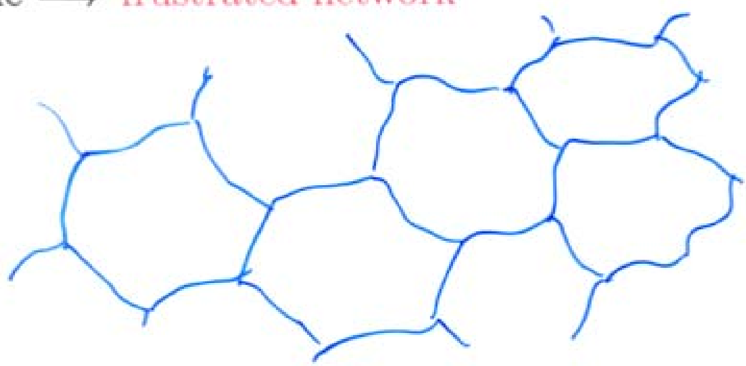
- Quintessence from extra dimensions (e.g. Albrecht et.al., 2001)
  - A 5D world: $G_{MN} \to g_{\mu\nu}, g_{\mu 5}, g_{55}$
  - Finite fifth dimension $\Longrightarrow$ $g_{55} \sim$ size ("radion" field)



  - Translational invariance $\Longleftrightarrow$ massless radion
  - Small breaking by brane attraction/repulsion, Casimir energies, etc. $\Longrightarrow$ small radion mass
  - Claim: in 6D models with large (ADD) extra dimensions, radion can play the role of quintessence, naturally

Domain Walls I

- Another altenative: domain walls (Friedland, Murayama, MP, 2002)
  - Exist in any EFT with multiple, discrete, degenerate vacua
  - Form in the early Universe via Kibble mechanism (consequence of causality)
  - CMB constraints require $> 10^6$ walls in the present Hubble volume $\Longrightarrow$ frustrated network



  - The symmetry breaking scale ~ 1 MeV $\Longrightarrow$ SUSY can be used to ensure radiative stability
  - Equation of state: $w = -2/3 \Longrightarrow$ ruled out by data???

Conclusions

- SM particles constitute only about 5% of the Universe
- Theoretically motivated BSM models can provide good candidates for dark matter – another 25%
- However, abundance predictions are very model-dependent
- The remaining 70% – dark energy – could be vacuum energy, present in SM and any BSM model
- All particle physics models predict too much vacuum energy, by many orders of magnitude
- The observed energy scale of dark energy is simply related to the weak and Planck scales, but no explanation
- Sensible particle physics models of quintessence can be built, but radiative stability has to be ensured